BNFL Inc.

# Section 3.5

# Cooling Water Contamination

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# Cooling Water Contamination

## 3.5.1 Work Identification

This section demonstrates an application of the integrated safety management process to an example of cooling water contamination. This report focuses on the control of hazards associated with a failure of the cooling coil in a high level waste (HLW) blending tank resulting in the introduction of tank liquor into the intermediate cooling water system.

The HLW feed blending vessels (V32004A/B) are provided for receiving, blending and sampling the HLW prior to transfer to the melter feed preparation vessel tank. Each blending vessel has been sized to contain two days worth of feed at a melt rate of 1.5 metric tons (t) of glass per day. The vessels are cooled by a closed loop cooling water system with cooling water circulated through coils immersed in the tank contents. The cooling coil has been postulated, in this example, to fail such that the cooling water becomes contaminated.

### 3.5.1.1 Key Process and Design Parameters

The function of the blending vessels is to contain and blend three different waste streams (solids portion from envelope B/D, Sr/TRU solids, Cs/Tc concentrate) prior to use in the HLW melter. These waste streams contain the majority of the transuranic, cesium and technetium contents after separation from the bulk of the tank farm waste. The dual vessels allow for one tank to operate in the receipt and blending mode while the contents of the other vessel are undergoing sampling, analyses and discharge. The vessels provide storage for two days worth of melter feed. **Design Assumptions.** (BNFL 1998c). The general flow of material into the tanks is shown in Figure 3.5-1

Heating of the vessel contents occurs through absorption heat from adjacent hot equipment and/or radioactive decay heat. This heat is removed by cooling coils that are part of a closed loop cooling water system to maintain process control. The normal operating temperature of the tank is 122 °F (50 °C). Pneumatic reverse flow diverters are used to pump the contents to the HLW feed blending vessels. Pneumatic pulsed jet mixers maintain a homogenous mixture. The vapor space of the tank is maintained at a slightly negative pressure relative to the process cell by the process vessel vent system (PVVS). This vessel ventilation system will provide removal of any vapors, aerosols, and/or gases that are generated. **Design Assumptions** (Ref. DWG. PR 00030, Rev. A).

The blending vessels are 6 ft (1.8 m) in diameter and 10.5 ft (3.3 m) high, with a total volume of 1,800 US gal (6.88 $m^3$) and an operating volume of 1,430 US gal (5.4 $m^3$) (DWG. PR00030, Rev. A). Since the cooling coil is assumed to be filled with vessel liquor in the postulated event sequence, the volume of the cooling coil (1 m3, see Section 3.5.2.2) is the controlling factor for this hazard and the dimensions of the vessel do not influence the analysis.

Plant cooling water provides cooling to the vessel and its contents during facility operation to maintain the liquid at the desired process temperature. There is a closed cooling water loop that circulates through the in-vessel coil, and then through heat exchangers in the operating area where heat is transferred to the plant cooling water system and ultimately to the cooling towers. **Design Assumption**.

While the HLW Feed Receipt and Pretreatment PFD (Ref. DWG.PR 00030, Rev. A) shows only one cooling coil, there will be more than one coil. Coil failure is not expected, but the economic risk associated with slowing the plant processing rate and replacement cost of the entire vessel far outweighs the cost of installing an additional (or more than one additional) cooling coil. **Design Assumption.**

Current plans call for pretreating the entire inventory of tanks 241-AZ-101 and 241-AZ-102, with the resulting cesium and technetium nitrate concentrate to be stored in the Tc and Cs Concentrate Storage Vessel, V24007. The Cs and Tc inventory of this vessels, coupled with the flowsheet data (Ref. W327-SA00001), identified the vessel contents to be considered in the Loss of Cooling to Cs storage vessel, Section 3.2. The inventory in vessel V24007, if it were transferred to V32004A/B, is bounding in terms of gamma activity for this example.

The properties of the liquid in V32004A/B are discussed in Section 3.2 (Example No. 2). This liquid is based on 100 percent recovery of cesium and technetium from tanks 241-AZ-101 and 241-AZ-102. The tank inventories are shown in Table 3.5-1. The Cs/Tc levels have been decayed to 2008, the starting date for HLW vitrification. The postulated liquid has a specific activity of $1.89 \times 10^5$ Ci/m$^3$ for direct radiation exposure. This is the bounding waste that may be received in the V32004A/B vessels. The bounding, gamma activity waste is the Cs/Tc concentrate since:

- the Cs/Tc storage vessel is one of the upstream process feeds,
- other waste feeds that would dilute the Cs/Tc concentration may not be available for further processing,
- direct radiation exposure of the facility worker is the consequence, and
- cesium is the major contributor of penetrating radiation.

**Table 3.5-1. October 1998 Best Basis Inventory (Assumes all activity recovered)**

| | **Decayed to January 1, 1994** | | | **Decayed to 2008** | | |
|---|---|---|---|---|---|---|
| | $^{134}$Cs (Ci) | $^{137}$Cs (Ci) | $^{99}$Tc (Ci) | $^{134}$Cs (Ci) | $^{137}$Cs (Ci) | $^{99}$Tc (Ci) |
| 241-AZ-101 | 43,400 | 7,430,000 | 1,100 | 391 | 5,390,000 | 1,100 |
| 241-AZ-102 | 41,200 | 4,320,000 | 599 | 371 | 3,130,000 | 599 |
| Total | 84,600 | 11,750,000 | 1,699 | 762 | 8,520,000 | 1,699 |
| Specific Activity[a] Ci/m$^3$ | 1,880 | 261,000 | 37.8 | 16.9 | 189,000 | 37.8 |

[a] Specific activity assumes all activity is initially stored in the 11,800 US gal (45 m$^3$) operating volume of the Cs storage vessel (Example No. 2) **Design Assumption**

Processing of only Cs/Tc concentrate, without dilution by any other HLW stream and incorporation into the glass at the listed waste oxide loading (Ref. Contract No. DE-AC06-96RL13308-Mod. No. A006), will result in glass that exceeds the 1,500-watt-per-canister specification by approximately 5%. The 1,500-watt-per-canister equals 180 Ci/L cesium-137, while the glass from processing only Cs/Tc concentrate will result in 189 Ci/L. Calculations were performed using only Cs/Tc concentrate in the HLW feed blending vessel, without any dilution or mathematical correction, as a conservatism (Smith 1999). In actuality, if only Cs/Tc concentrate was to be vitrified, some modification to the glass formulation would be made.

### 3.5.1.2 Interfaces

Normal process operational requirements for both blending vessels include cooling, mixing, ventilation, and transfer capability. In the present V32004A/B design, interfaces exist with the systems in the balance of the facility which provide inlet and outlet of vessel contents, vessel structural support, cooling water flow, ventilation, and the air supply for vessel mixing.

Waste received by the V32004A/B vessels comes from the Envelope D receipt vessels, Sr/TRU Precipitate vessel, and Cs/Tc concentrate storage vessel. Although the off-specification resin from the Cs and Tc resin recovery system is shown on the PFD (BNFL Inc. 1999d) to feed into V32004 A/B, the flow sheet has been changed so that resin recovery no longer interfaces with LAW vitrification. This change has no effect on either initiating or modifying the events postulated in this example. The contents of the V32004A/B vessels are fed to the HLW melter feed preparation vessel. **Operational Assumption.**

The plant compressed air system provides motive power for the pulsejet mixers and reverse flow diverters. The PVVS removes vapors, aerosols, and gases evolved from the vessel contents, and maintains the vessel at a negative pressure with respect to the cell. The Cell ventilation system maintains the cell at a negative pressure with respect to the occupied areas of the facility and provides some additional cooling to the vessel.

Cooling of the HLW blending vessels is through a closed loop system that contains the in-vessel coil. Cooling water recirculates through the in-vessel coil where it absorbs heat and then flows through a heat exchanger where the heat is rejected to the plant cooling water system. The plant cooling water system is the main cooling system that contains the cooling towers. Pumps, valves and provisions for adding make-up water of the closed cooling water system are located outside of the cell for access during operation and maintenance. The volume of the submerged cooling coil is estimated to be 260 US gal (1 $m^3$), while the closed loop cooling system volume is estimated to be 1,320 US gal (5 $m^3$). **Design Assumption.** The pressure in the cooling coil is maintained above the pressure in the vessel at all times by the provision of a make-up head tank system which feeds both inlet and return legs of the coil. **Design Assumption**.

### 3.5.1.3 Operating Environment and Setting

Both of the vessels V32004A/B operate continuously, with a fill to blend to discharge cycle time of four days. The vessel contents are constantly being mixed and will have variable pH and solids concentration levels depending on the particular waste blend being processed. The desired process temperature is 122 °F

(50 °C). **Operational Assumption**. There is no planned maintenance of either vessel due to the high radiation levels from both the vessels contents and other vessels within the cell.

The out-of-cell components will either be located in a segregated area ventilated by the C3 ventilation system or be in the C2 operating area. There they will be exposed to the range of temperature, humidity, and pressure associated with either of these operating areas. It is unlikely that the out-of-cell components will be exposed to corrosive chemicals in the building atmosphere, but one of the options under consideration for treating the cooling water is the addition of 0.1M nitric acid or sodium nitrate solution for corrosion control.

The main plant cooling water system will be exposed to the range of environmental conditions present on the Hanford Site. Significant conditions are those which could adversely impact the cooling tower and possibly lead to cessation of the cooling water supply, i.e., volcanic ash, high winds, dust.

Both of the V32004/B vessels are located in the LAW Receipt Cell, which is a C5 area. There are 4 neighboring vessels: two evaporator feed vessels, one evaporator concentrate buffer vessels and one steam condensate transfer vessels. None of these vessels is anticipated to have an effect on either initiating or modifying the events in this example.

The facility structure (vessel foundation, cell structure) provides secondary containment and shielding.

The operating mode of the two (or more) cooling coils has not been established. They could be operated each at 50%, or one at 100% and the other on standby. It is assumed for this example that one coil will be at full operation and the other on standby. **Design Assumption.** The analysis is not strongly sensitive to this assumption.

Outside of the cell, the closed cooling water loop flows through an operating area that requires access by facility workers for operation and maintenance. Instrumentation, valves, pumps, heat exchangers to the plant cooling water system, piping, etc. are also located in this area. **Design Assumption.**

The TWRS-P process under consideration in this worked example is cooling of the V32004A/B vessels by one or more of the associated cooling coils and associated cooling water system. The waste assumed to be contained in the vessels is the liquor from the Tc and Cs concentrate storage vessel that has an upper bound gamma activity. The closed cooling loop process water flows from the vessel, out of the process cell, to the pump(s)/valve(s), through a heat exchanger and returns to the vessel. The heat exchangers transfer heat to the plant cooling system. If radioactive liquor from the vessel were to leak into a cooling coil, the radioactivity would be transferred within the closed loop cooling water piping to the operating area where a worker could be exposed to direct radiation. The source term and assumed system geometry creates a bounding, or near bounding, direct radiation dose consequence to the facility worker by estimating an exposure rate based on the highest gamma radiation liquor being introduced into the largest volume components.

### 3.5.1.4 Applicable Experience

For many years at both BNFL and DOE facilities, cooling coils have been used in high level waste tanks as a means to cool liquids having a high heat generation rate.

BNFL's Sellafield Site has 1) both single-loop cooling water systems recirculating through cooling towers and 2) primary secondary systems in which heat removed from the process, is rejected via an intermediate heat exchanger cooled by water circulating through open cooling towers. Primary-secondary systems effectively preclude the risk of activity breakthrough to the open cooling towers if a cooling coil failure occurs. They also facilitate control of the water quality in the closed loop, significantly reducing the risk of a cooling coil failure.

Primary/secondary systems are used in the Thermal Oxide Reprocessing Plant (THORP), the Waste Encapsulation Plant, the ILW Storage Silos, the Windscale Vitrification Plant, and the Enhanced Activity Removal Plant (EARP). Single loop open-recirculating systems are used in the Highly Active Liquor storage facilities (B215), the Windscale Vitrification Plants, and the older reprocessing plants.

There is a large amount of historic evidence from the B215 Plant on the operation and probable failure rates of cooling coils in a highly active environment. To date there have been 2 cooling coil failures with holes >0.5 mm and 9 coil failures with pin-holes (<0.5 mm) in over 3000 coil years of operation. Water side corrosion has been the only failure mechanism and has only occurred in the B215 plant. There have been no coil failures in any of the other Sellafield plants.

All of the above failures have been in tanks with multiple coils i.e., more than 2 coils per tank. To avoid overcooling the process liquor, the coils have been used intermittently, including some long periods out of use. The first coil failure was recorded in the 1970's in a coil that had been out of use for more than a year. There have been no coil failures recorded in any cooling coils that have been in continuous service in any Sellafield plant. (Continuous service does not mean without any interruption of flow but that the interruptions have only been for a matter of days or a few weeks rather than several months or longer.) There have been no coil failures on primary-secondary systems irrespective of the continuity of service.

BNFL has developed comprehensive procedures for managing coils that are not in service. This includes drying out the coil, and then cocooning; i.e., they are isolated, pressurized with air, and connected to a silica gel trap for moisture absorption and detection. The air pressure is measured by two independent pressure instruments. Preparations to bring the coil into service include:

1. Emptying the vessel containing the cocooned coil
2. Performing a pressure decay test using the independent pressure measuring instruments
3. Depressurizing the coil through an activity-in-air monitor
4. Physically connecting the coil outlet to the suspect active cooling water effluent route
5. Monitoring of the effluent for a period
6. Finally, returning the coil and vessel to normal service.

All BNFL's cooling water systems, whether single loop or primary/secondary, are fitted with gamma activity monitoring in cooling water monitoring systems. Depending upon the application, the cooling water return line may flow into a delay tank, the outlet of which is fitted with a shutoff valve actuated by the gamma activity monitor for automatic isolation. The delay tank is sized to provide the required system response time.

Three important factors emerge from the Sellafield experience of cooling coil failures:

1. The only failure mechanism has been water side corrosion giving rise to small holes.

2. If a hole develops while the coil is in service, then it will either be detected by the cooling water gamma monitors or by the level in the vessel rising (if the hole is big enough – about 5 to 10 mm).

3. Even if an unrevealed failure occurs during an interruption of cooling water flow, the dose resulting from an assumed 2-hour exposure to the operator is not very significant, providing the interruption is not too long. For instance, a calculation based upon the WVP Line 3 feed tank coils shows that the dose would be 63 mrem if the interruption was 9 hours and the hole size was as large as 10 mm. The radionuclide content in the WVP case is much greater than in TWRS-P based on comparison of tank self-heating rates on loss of cooling (Lihou 1997).

# 3.5.2 Hazard Evaluation

For this example, coil failure could lead to two different scenarios: contamination of the cooling water and overfilling of the vessel, depending on the direction of flow. Vessel overflow is a separate hazard, which is recorded as an **Open Issue** pending assessment. Contamination of the cooling water could occur as either a major or minor release. Initiators of coil failure include corrosion, seismic event, and weld failure.

## 3.5.2.1 Hazard Identification

The basis of this example is the process as described in the Initial Safety Analysis Report (ISAR) dated (BNFL 1998b), the Hazards Analysis Report (HAR) (BNFL 1997), and the Part A Technical Report (BNFL 1998c).

While the ISAR lists many locations and possibilities for pipe breaks, leaks due to corrosion, erosion or misaligned connectors, and loss of cooling water flow to various equipment, it did not list cooling water contamination as a potential accident. However, in the HAR, contamination of cooling water is listed as a potential hazard many times. Since the HAR investigated the hazards per functional area of the plant, cooling water contamination resulting from a cooling coil break or leak in a vessel was not specifically analyzed. However, “Activity in the cooling water” was identified as a result of different initiating events within the Low Activity Waste Feed Receipt Evaporator, Entrained Solids Removal and Melter areas. Listed safeguards for prevention or mitigation included:

a. Closed-circuit cooling (via coil) water system with isolation and monitoring facilities, separate from the cooling towers; or a minimum of a primary and a secondary loop,

b. Adequate valve and isolation arrangements,

c. Monitoring of activity level in the cooling water or LP steam,

d. Pressure gradient from the service into the process, and

e. Cooling water volume monitored for leak detection.

The HAR was based on a conceptual design level of design. The need for a more detailed hazard study as a part of the developing design process was stated.

The bounding source term to be contained within vessels V32004A/B has been identified as the Cs/Tc concentrate. The physical parameters and connections to the tank have also been listed. The specific hazard to be analyzed is direct radiation dose to operators and co-located workers from cooling water contamination due to failure of a cooling coil.

### 3.5.2.2 Event Sequence

Two primary event sequences have been identified which could give rise to consequences associated with failure of a cooling coil. These are:

1. Coil fails during service and activity enters coil and is transported to operating area

2. Standby coil fails while shutdown and isolated and activity enters coil. This is then transported to operating area on coil energization.

Procedural controls in place in BNFL's existing plants concerning the isolation and subsequent reenergization of standby cooling coils are expected to apply to TWRS-P. This means that the probability of a significant dose to an operator on reenergization would be very low, even in the absence of any engineered protection (see Section 3.5.1.4). Restart would be carefully controlled. It is not considered that this event is likely to be the main driver for provision of engineered protection systems. Therefore, it has not been selected for analysis at this time, but will be fully evaluated as part of design development. **Open Issue**.

Failure of a coil in service would not normally give rise to significant consequences. This is because the cooling water is always maintained at a higher pressure than the vessel, and so migration of activity into the coil would be a very slow process, and would be readily revealed by routine monitoring or standard installed detectors before significant consequences had occurred. See Section 3.5.1.4. Again, it is not considered that this primary sequence is likely to dominate risk or the requirements for engineered protection, and it will be fully evaluated during later design development. **Open Issue**.

A development of the sequence does have the potential to give rise to more significant operator consequences. If an in-service coil were to fail and then be depressurized or to fail while depressurized for a sufficient time to allow significant activity to enter it, then a significant dose rate could result in the loop on restart. The procedural and management controls applying to a maintenance outage are unlikely to be as rigorous as those applying to a standby coil startup. If consequences were severe, a greater requirement for engineered protection to manage risk would be predicted. This event sequence has been chosen for analysis.

### 3.5.2.3 Unmitigated Consequences

It is assumed that the failed coil is depressurized for long enough for it to fill with the Cs/Tc concentrate contained within the HLW blending vessel. (This is conservative, since it is much more probable that only a fraction of the coil would fill.) Restart of the cooling water system then pushes an undiluted slug into the heat exchanger, where a facility worker is exposed for 12 minutes. The basis for the 12-minute exposure was an assumed 22 gpm (5 $m^3$/h) flow rate and a 265 US gal (1 $m^3$) slug volume **Design Assumption**. Therefore, 20% of an hour is required for all of the slug to pass one point. Recirculation within the cooling loop is assumed to cause thorough mixing, with a dilution factor of 5, after one loop volume has been circulated. The worker is conservatively assumed to be exposed to the diluted solution being circulated through the heat exchanger for the remainder of the 8-hour period. The gamma shielding code “Microshield”, Version 5 was used to conservatively estimate the worker dose. Due to the high cesium concentration, the exposure rate at 3 ft (1 meter) from the heat exchanger is estimated to be 5,400 rem/h for the undiluted slug (0.89 rem/h at 100 m) and to be 2,200 rem/h after dilution (0.36 rem/h at 100 m). Results for the unmitigated cooling water contamination event are shown in Table 3.5-2. (Ref. Calc-W375-HV-NS00002).

**Table 3.5-2. Unmitigated Dose Consequences**

| Receptor | Dose (rem CEDE) | Severity Level |
|---|---|---|
| Facility Worker[a] | 17,000 | SL-1 |
| Co-located Worker[a] | 3 | SL-3 |
| Public[b] | N/A | N/A |

[a] There is no released material to the environment, so consequences are due to direct radiation shine.

[b] Per K70C505, Rev. 0, “Code of Practice for Accident Analysis Process”, potential exposure to public from direct radiation is not calculated.

It is not expected that doses approaching this would be received in the event sequence analyzed, since a large enough hole to allow coil filling would almost certainly have revealed itself through vessel level rise; however, consequences in excess of SL-1 lower limit of 25 rem would be predicted.

### 3.5.2.4 Frequency of the Initiating Event

A range of 0.001 to 0.02 failures per year are cited in the Sellafield Database (BNFL plc 1998). These failure rates are dominated at the top end by a group of failures which have occurred in the B215 HA storage plant. The cooling system there is an open loop recirculation system. Substantial experimental work has been carried out on this group of coil failures. That work has shown that the corrosion mechanism is crevice corrosion. It has also shown that the following conditions are required:

- A receptive site for crevice attack (i.e., poorly finished weld)
- Presence of chloride ion
- Presence of sufficient hydrogen peroxide to initiate the crevice corrosion.

Hydrogen peroxide is a radiolysis product. The chloride ion is from drawing salt air into the open cooling towers.

If the water is allowed to stagnate, then finely divided solids deposit and absorb the chloride ion, increasing the risk of attack. If the water is kept flowing, then the deposits are prevented and neither hydrogen peroxide nor chloride accumulates. A primary/secondary cooling system prevents these conditions from occurring in the closed loop. Moreover, the water quality can be maintained constant.

In TWRS-P the closed-loop unit will be filled with demineralized water and dosed with sodium nitrate. Hence it is conservative to claim a failure rate of 0.001/y for a high integrity coil in a closed loop system. **Design Assumption**.

For the event to occur, a failed coil must become depressurized. The majority of maintenance activities on the primary cooling circuit will not depressurize the coil, since a head tank keeps it pressurized at both feed and return legs. It is conservatively assumed that one maintenance operation per year leads to or requires depressurization of the coil. Operational experience would indicate a lower frequency.

The probability that the coil is failed at the time of this depressurization is conservatively taken as 0.001. This very conservatively assumes that no modes of revealing the coil failure to the operator are in use or have been effective, and the failure has the opportunity to become longstanding:

No credit is taken for any administrative controls on coil restart. The initiating event frequency is therefore:

1 depressurization/year x 0.001 probability that coil is failed = 0.001/year

### 3.5.2.5 Common Cause and Common Mode Effects

A seismic event could be a common cause for allowing a coil to fill with vessel liquor. Subsequent restoration of power to the cooling water pumps after the seismic event could cause the slug of liquor to be transferred to the operating area.

### 3.5.2.6 Natural Phenomena Hazards and Man Made External Events

#### 3.5.2.6.1. Natural Phenomena

Natural phenomena hazards (NPH) and their treatment on a plant-wide basis are included in Section 2.10. **Design Assumption**. Of these, seismic events are a potential initiator for cooling water contamination. However, since vessel cooling is only provided for process control, post seismic operation is not required for safety reasons.

#### 3.5.2.6.2. Man Made External Hazards

Similarly, man-made hazards and their treatment on a plant-wide basis are also discussed in Section 2.10. There are no man-made hazards that uniquely affect this event.

## 3.5.3 Control Strategy Development

### 3.5.3.1 Controls Considered

The following controls were considered to prevent (P) or mitigate (M) the consequences of a cooling coil leak and are marked appropriately:

- <u>High Integrity of Coil</u> (P). A high integrity coil would have design features that would be highly resistant to anticipated failures due to the vessel environment or seismic events. Features such as a thicker wall for enhanced erosion and corrosion-resistant and special alloy construction are some foreseen design features. Coils are also routinely maintained above vessel pressure by a gravity feed water make-up system.

- <u>Use of Vessel Cooling Jackets</u> (P). Cooling jackets on the outside of the vessel have the potential to provide a higher integrity means of cooling the vessel contents than internal cooling coils. (This is based primarily upon vessel wall thickness.) To remove heat from the vessel contents, cooling water would be circulated through an external-cooling jacket instead of an internal cooling coil.

- <u>Shield Cooling Loop</u> (M). Providing shielding for the portion of the cooling loop that is external to the shielded process cell will mitigate potential exposure to workers in the operating area. Shielding is considered to be shield walls to protect an area and not individual shielding wrapped or placed onto components.

- <u>Gamma Detector on Cooling Line</u> (M). This control strategy element will provide a detector that would detect gamma activity in the cooling water. The detector would be located on the cooling line outside of the cell to avoid high background and ensure relative ease of maintenance and calibration. In-cell detectors are not practical. The element was deemed to be either administrative, in that a procedure would be required to establish the steps to be performed in the event of activity in the cooling water, or automatic, via some type of control logic.

- <u>Area Radiation Monitor</u> (M). This control strategy element will provide a detector for gamma activity in the operating area, as may result from a failed cooling coil, and an alarm to alert operators to evacuate the area. The element was deemed to be administrative in that a procedure would be required to establish the steps to be performed in the event of high activity in the operating area.

- <u>Interlock on Cooling Line</u> (M). This control strategy element would provide an automatic control to isolate the cooling water on detection of activity in the cooling water. Isolation valves located outside the cell would provide this action. The isolation valves are to shut upon loss of power, thereby adding a fail-safe action to this control strategy element.

- <u>Startup Procedures for Coil</u> (M). This control strategy element would develop procedures that govern activating a cooling loop once it has been shut down and depressurized for maintenance. The procedure would require that a complete pre-operative checkout be performed prior to use of the coil. The pre-operative checkout could include such techniques as pressure decay testing, strictly limited volume flushing, monitoring for activity, etc. This would prevent transport of a slug of activity into the operating area.

- <u>Tertiary Cooling Loop</u> (M). This control strategy element would provide a tertiary loop that would be contained within the process cell, to the extent practicable. The secondary loop would exchange heat with the tertiary loop at the cell boundary. This would preclude the potential for worker exposures from this scenario

- <u>Delay Tank</u> (M). This control strategy element would add to the cooling loop a delay tank with sufficient capacity to delay the cooling water from entering the operating areas after a high gamma level has occurred until isolation is achieved. The delay tank would be located outside of the cell for cost avoidance.

- Divert Cooling Water to a Standby Tank (M). This control strategy element would automatically divert the cooling water flow to a holding tank on detection of high gamma activity in the cooling water. The standby tank would be located in a non-occupied area.

### 3.5.3.2 Control Strategy Selection

Control strategy selection was based on a two-step process; first, clearly unrealistic control elements were deleted; second, engineering tradeoffs were considered to further down-select the options, and a preferred control strategy was selected.

#### 3.5.3.2.1. Step 1 (Initial Screen)

The merits of each potential control strategy were considered, primarily against the following set of criteria:

- Effectiveness
- Practicality
- Reliability
- Demonstrability
- Compliance with laws and regulations
- Ability to comply with the top level principles of DOE/RL-96-006 General Radiological and Nuclear Safety Principles (DOR-RL 1998) (in particular, the use of proven engineering practice, ease of providing inherent/passive safety features, radiation protection features, and avoidance of undue reliance on human actions).

The results of this evaluation are shown in Table 3.5-3.

**Table 3.5-3. Initial Evaluation**

| Control | Advantages | Disadvantages | Compliance with Top Level Principles | Further Consideration in Control Strategy |
|---|---|---|---|---|
| High Integrity of Coil | Easy to implement, practical, passive | Needs controlled environment to be effective | Yes | Yes |
| Use of Vessel Cooling Jacket | Greater wall thickness<br>Less corrosion susceptibility than coil, practical, passive | Unknown whether required heat removal rate can be achieved, more complicated fabrication | Yes | No – open item for evaluation post example |
| Shield Cooling Loop – portions outside cell | Passive, protects worker, demonstrable | Hinders access for maintenance, requires installation of remotely operated drain/flush | Partial maintenance and recovery requires procedural control | Yes |
| Gamma Detector on Cooling Line | Early warning through alarm, easily made redundant, proven practice | May require shielding, calibration required | Partial – requires operator response for effectiveness | Yes |
| Area Radiation Monitor | Provides warning to facility worker, industry practice, regulatory requirement | Requires operator action to evacuate, does not effectively mitigate exposure from large dose | Partial – requires operator response for effectiveness | Yes |
| Interlock with Gamma Detector on Cooling Line | Stops flow of contaminated material, easily depicted for reliability, BNFL practice at Sellafield | Requires active system | Yes | Yes |
| Startup Procedures for Coils | No system modifications required, practical, able to respond to variable conditions | Relies on administrative control , remote startup may not be practical | Partial – relies on human actions | Yes |
| Tertiary Cooling Loop | Keeps potentially contaminated cooling water loop in cell | Requires another fully active system, maintenance of in-cell components impractical, costly | No – active system, neither maintenance or recovery is ALARA | No |

**Table 3.5-3. Initial Evaluation**

| Control | Advantages | Disadvantages | Compliance with Top Level Principles | Further Consideration in Control Strategy |
|---|---|---|---|---|
| Delay Tank | Allows containment of contaminated cooling water, could be in- or out-cell, BNFL practice at Sellafield | Requires active interlock and shielding on location in restricted access shielded area to be effective | Yes – active system required to make it effective | Yes |
| Divert to Standby Tank | Contaminated water is contained, demonstrable | Requires additional or available tank and piping, requires limitation of make-up water volume, requires detection and diversion system which offers no safety advantage over the detection and interlock system | Yes - active system required to make it effective | No. An effluent holding and sentencing system for restart of isolated coils is a normal system provision |

Both the tertiary cooling loop and diversion to a standby tank were not considered viable for further consideration. The tertiary cooling loop would provide a second layer of defense, but requires placement of many active components into a highly radioactive environment, requiring remoting of all controls, maintenance, and operational checks. With the radiation protection concerns and significant cost also associated with this control strategy element, as well as the existence of many other advantageous control strategy elements, the tertiary cooling loop was eliminated.

Diversion to a standby tank requires the floor space, capital and maintenance cost for another vessel. Its function of providing a holding point for the now contaminated cooling water can be provided by a discharge point to an active drain, which will be a provision of the closed cooling loop. The diversion to standby tank was therefore eliminated.

The following controls remained to be considered in formulation of the control strategy to be adopted:

- High Integrity Coils
- Shield cooling loop outside of cell
- Gamma Detector on Cooling Line
- Area Radiation Monitor
- Interlock on Cooling Line
- Startup Procedures for Coils
- Delay Tank

The high integrity coil, the gamma detector with alarm, area radiation monitor, and startup procedures, originally identified as control strategy elements, can function as independent control strategies. The remaining control strategy elements; the gamma detector on the cooling line linked to an interlock, the delay tank, and shielding for the tank and piping should be combined to form one control strategy. The interlock without a delay tank requires extremely rapid response gamma detector and isolation valves and may cause pressure transients in the coil, which themselves could lead to coil failure. A delay tank by itself only adds volume to the cooling loop. A detector is required to activate the interlock, but by itself would only sound an alarm. Shielding of the delay tank and associated piping, if they are used as part of the control strategy, would mitigate worker exposure.

### 3.5.3.2.2. Step 2 (Engineering Screen)

The preferred strategy was then developed through an engineering evaluation of the alternatives. This review took account of the following considerations to ensure a comprehensive approach in the context of other hazards and the overall design:

- Introduction of secondary hazards

- Impact on safety features provided to protect against other hazards

- Impact of other hazards upon the control strategy

- Robustness to other fault conditions and environments (including seismic and other design basis events)

- Passive or active, if active automatic or administrative/procedural – order of preference

- Robustness of any administrative controls required
- Cost
- Operability
- Maintainability
- Ease of justification (e.g., consistency with proven technology)

The considerations are presented in Table 3.5-4.

**Table 3.5-4. Engineering Screen**

| Criterion | High Integrity of Coil | Gamma Detector on Cooling Line | Area Radiation Monitor |
|---|---|---|---|
| Introduce Secondary Hazards | No | No | No |
| Impact on Safety Features Provided to Protect Against Other Hazards | No | No | No |
| Impact of Other Hazards upon the Control Strategy | No | Impacted by loss of power or loss of flow | Impacted by loss of power (unless battery backup) |
| Robustness to Other Fault Conditions and Environments | Yes – if seismically qualified | No – sensitive to loss of power and flow | No – sensitive to loss of power<br>Yes – with battery backup |
| Passive or Active | Passive | Active, requires prompt operator response to affect mitigation | Active, automatic |
| Robustness of Any Administrative Controls Required | Simple, QA during construction | No significant complexity, well understood | No significant complexity, well understood |
| Cost | No significant cost increase | Some cost – gamma detector not expensive | Normally required for operating areas – no cost differential |
| Operability | Well proven | Well proven | Well proven |
| Maintainability | Maintenance not required | Inclusion of detectors will require additional maintenance activity | Inclusion of detectors will require additional maintenance activity |
| Ease of justification | Proven, much experience | Proven technology | Proven technology |
| Consider Further | Yes | No | Yes |

**Table 3.5-5. Engineering Evaluation.**

| **Criterion** | **Gamma Detector Interlock, Delay Tank, Shielding** | **Startup Procedure for Coils** |
|---|---|---|
| Introduce Secondary Hazards | No | No |
| Impact on Safety Features Provided to Protect Against Other Hazards | Isolation of cooling water is a potential cause of vessel self-boiling **-Open Issue-** | No |
| Impact of Other Hazards Upon the Control Strategy | No – isolation valves fail closed on loss of power | No |
| Robustness to Other Fault Conditions and Environments | Isolation valves fail safe on loss of power | Yes – well trained workers can respond to all identified situations |
| Passive or Active | Active, automatic | Active |
| Robustness of Any Administrative Controls Required | No significant complexity | Some complexity, but no significant time or other constraints |
| Cost | Significant cost involved with installation of entire system | None |
| Operability | Well proven | Well proven |
| Maintainability | Inclusion of active components will require additional maintenance activity | None required |
| Ease of Justification | Proven technology | Proven method |
| Consider Further | Yes | Yes |

#### 3.5.3.2.3. Control Strategy Selected

The selected control strategy is:

- High integrity cooling coil as part of the closed circuit cooling loop – This provides prevention by both a direct physical barrier and administrative control of cooling water quality to prevent corrosion. The cooling loop is pressurized as a part of BNFL design practice.

- Startup procedures for coil restart after shutdown will prevent transport of a slug through the cooling loop and worker exposure.

- A minimum of one on-line gamma detector, interlocked to stop water flow, and delay tank to prevent heat exchanger and pumps in operating area becoming contaminated.

- Area radiation monitors to detect radiation field from activity breakthrough to cooling coils.

### 3.5.3.3 Structures, Systems, and Components that Implement the Control Strategy

- High integrity closed-loop cooling coil
- Activity breakthrough gamma detectors, interlock, and delay tank system
- Area radiation monitors with alarm.

A sketch of the selected SSCs, as they are proposed to be installed, are shown on Figure 3.5-2.

## 3.5.4 Safety Standards and Requirements

### 3.5.4.1 Reliability Targets

The Severity Level for the Full Coil case event is SL-1 for the facility worker. The reliability target for the overall control strategy is therefore $1x\ 10^{-6}$/y. This target must be achieved by a combination of the preventive and mitigative elements of the strategy.

#### 3.5.4.1.1. Cooling Coils

The Sellafield experience indicates that cooling coil failure frequencies as low as approximately 0.001/y are now achieved. Construction of a cooling coil using the best material to withstand operating environments, increased wall thickness for corrosion and erosion allowances, fabrication without welds, and rigid quality assurance throughout construction will result in a high-integrity coil. Use of a high integrity coil and proper attention to water chemistry in the intermediate cooling loop should provide increased performance by one to two orders of magnitude. Hence, a 0.001/y failure rate for a high-integrity cooling coil as a preventive measure is readily achievable.

#### 3.5.4.1.2. Gamma Detector, Interlock, and Delay Tank

Dual gamma monitors will be located on the cooling water line exiting the cell. The probability of failure of a single gamma detector has been determined to be $4\ x\ 10^{-2}$/y, based on both Sellafield and Savannah

River experience and an annual functional test. Failure modeling of similar, redundant components requires the use of β-factor values. The β-factor for redundant components which fail in a revealed manner, as the gamma detectors will do, is 0.06. The dual gamma detector failure probability is calculated by individual failure probability times β to be 2-4 x $10^{-3.}$ The failure probability of the interlock is bounded by the gamma detector failure probability.

### 3.5.4.1.3. Startup Procedures

The proposed control strategy focuses on preventing gross failure of the cooling coils. It also is reliant on the "leak-before-break" theory which is very appropriate since Sellafield experience demonstrates that the coils always first develop minor pinhole leaks through corrosion mechanisms. Hence, the control philosophy also includes practices to prevent corrosion-inducing material in the cooling water, and techniques to detect coil failure when it starts. In particular, the administrative control strategy consists of:

- Operational controls that require a prolonged shutdown coil to be checked/tested for internal radioactive contamination before the cooling loop containing that coil is restarted for service (Sellafield operating evidence indicates that coil failure is more likely to occur in a shutdown, static system which remains that way for a long period of time.)

Failure of these administrative control provisions sufficient to cause significant failure of the cooling coil must achieve the remaining apportionment of the 1 x $10^{-6}$/y goal. The cooling coil integrity is targeted at 1 x $10^{-3}$/y. The probability of failure on demand of the gamma interlock system is given in Section 3.5.4.1.2 as 2.4 x $10^{-3}$. Therefore, the failure probability for these administrative features which further ensure that (a) coil pinholes do not start or at least do not grow to allow significant in-leakage of liquor, or (b) prolonged shutdown or coils are not used before a thorough check, will be more than adequate if it is 0-1 or below. This will give an overall frequency of 2.4 x $10^{-7}$.
This is considered readily achievable by a well-trained work force with good management procedures.

### 3.5.4.1.4. Radiation Monitor

Area radiation monitors are provided as an element of defense-in-depth mitigation. No frequency target is required or claimed.

## 3.5.4.2 Performance Requirements

Overall performance requirements of the control strategy for seismic events and aircraft strike must first be developed. The next sections describe the performance required of the elements of the control strategy to achieve the safety function.

### 3.5.4.2.1. Performance of the Strategies Against Design Basis Events

Seismic

A seismic event is a possible initiator of both a leak in a cooling coil and failure of circulation, which can result in the coils filling with liquor. It is necessary to ensure that this does not make a contribution to risk that could challenge achievement of the relevant target frequency for the event. The design basis seismic event, by definition, has a frequency of 5 x $10^{-4}$/y.

While low-range gamma detector could provide an indication of cooling coil contamination after a DBE, it would have to be seismically qualified to ensure its functionality. After a DBE, a full programmatic recovery action would be undertaken to ensure the integrity of all lines, inspect/repair/replace components, perform readiness review and operability testing. A probability of not correcting a fault caused by the DBE has been assigned a value less than or equal to $2 \times 10^{-3}$/y. This probability is termed the programmatic recovery factor, and is based, with some modification, on failure of a trained operator to perform the needed task of $3 \times 10^{-3}$/demand.

Since the SL-1 target frequency is $1 \times 10^{-6}$, the failure probability of the control strategy's prevention or mitigation should be less than or equal to the target frequency. By seismically qualifying the cooling coils, a failure probability equal to the DBE frequency of $5 \times 10^{-4}$ is obtained. Seismic qualification of the high-integrity cooling coil is selected due to the relative ease and low cost of qualifying this component. **Safety Function.** Application of the post-DBE programmatic recovery factor, with its maximum value of $2 \times 10^{-3}$, meets the target frequency of $5 \times 10^{-4} \times 2 \times 10^{-3} = 1 \times 10^{-6}$. (This assessment will also be valid for beyond design basis seismic events that will have a lower frequency.) The analysis takes no account of mitigation (which will ensure that the probability of cooling water contamination having SL-1 consequences is lower than $1 \times 10^{-6}$) and is therefore conservative. The seismic qualification of the cooling coil will ensure that the target frequency is not exceeded for any sub-design basis seismic event.

<u>Aircraft Strike</u>

The HAR (1998) derives a frequency for aircraft crash into the TWRS facility as $4.5 \times 10^{-6}$/y. It can be seen that area occupied by the HLW blending vessels and associated closed loop cooling system is much less than 10% of the pretreatment building. (Ref. DWG. SK-W375 PT-PL00006, Rev. A or 0-BE-TWRS-DK-199, Rev. P1). The pretreatment building is one of 5 buildings that will comprise the TWRS-P facility (Ref. DWG. W375-00002). The pretreatment building occupies less than 20% of the footprint of the entire facility. The probability of an aircraft crashing into the HLW Blending vessels and/or the closed loop cooling system is therefore much less than 2%. The overall probability of an aircraft crash causing a cooling water contamination event will be negligible at $9 \times 10^{-8}$/y, and need not be considered further.

### 3.5.4.2.2. High Integrity Cooling Coil

The cooling coils must maintain integrity to prevent a leak of the vessel contents to the cooling water. Seismic qualification of the coils will be required. The lead tank system must maintain coil pressure above vessel pressure.

### 3.5.4.2.3. Gamma Detector, Interlock, and Delay Tank System

NF 0007/1 is a BNFL design guide to detection of gamma activity in cooling water systems. The evaluation in this paper calls for a system similar to those in the NF, with requirements that:

- 1 out of 2 or 2 out of 3 in-line shielded gamma monitors be provided. The monitors should have high level alarms, trips, and recorders

- The monitors activate one or two fast close shut valves which are upstream of the heat exchanger/pump system

- A delay tank allows the valves to close before any significant contamination could reach the heat exchanger/pump system

- A head tank is provided to maintain a higher pressure in the cooling water loop than in the liquor. A shielding required for tank or its room will be developed when design detail permits.

### 3.5.4.2.4. Area radiation monitor

The area radiation monitor in the operating area must detect direct gamma radiation in the cooling water and initiate an alarm to alert personnel working in the area. The area radiation monitor must fail in a revealed manner. Use of the area radiation monitor will result in a reduction in worker dose during a significant leak event. A one-liter leak of vessel liquor into the cooling coil (0.1% of the full coil in the mitigated scenario) will have an exposure rate of proportionately the same amount, or 0.001 x 5,400 mrem/h = 5 rem/h. Since facility design and safety requirements do not exist to specify the setpoint of the alarm or the evacuation distance, a specific dose consequence is not calculated. However, a 10-minute evacuation time results in less than a 1-rem exposure. The instrument would in fact respond to dose rates only a small fraction of this.

### 3.5.4.3 Administrative Measures

Administrative measures required to assure the selected control strategy are as follows.

Normal Operations

Normal operations will be conducted in accordance with approved operational safety requirements and in strict accordance with administrative and procedural control. Operators will be trained and assessed on the conduct of normal operations. Operational procedures, routine schedules and records will augment training.

Arrangements for the examination, inspection, maintenance and testing of all ITS equipment associated with the cooling water system will be managed through a plant maintenance schedule. All maintenance activities will be carried out using appropriate maintenance instructions.

Operator Response

Operators will be trained to identify, diagnose and respond to abnormal operating conditions. Plant information will be relayed to the operator in such a manner to aid the operator in performing this duty. Typically, any deviation of the process from its normal operating condition will generate an alarm appropriate to its importance. This alarm will annunciate at the operator workstation or locally within the facility. Operational procedures will detail the:

- Actions the operator must perform to minimize the impact of the abnormality

- Sampling, analysis and disposal of contaminated water according to TWRS-P procedures, which will be developed in due course

- The followup actions required, when plant conditions have been stabilized.

### 3.5.4.3.1. Cooling coils

The cooling coil will undergo in-service pressure testing on an as-needed basis. **Operational Assumption.**

### 3.5.4.3.2. Gamma Detector and Interlock System

The low range gamma detector and interlock system will require periodic inspection, testing, and calibration. Radiation control technician support will be provided during these activities. An effective radiation protection program will govern all maintenance activities. **Operational Assumption.**

### 3.5.4.3.3. Water Quality and Restart Procedures

The water quality control program and procedures will be coupled with in-line instruments, sampling, calibration requirements, and laboratory quality assurance practices. Radiation control technician support will be provided during sampling and transport.

Operational controls that prevent a water filled coil from remaining in a stagnant condition will be developed and followed. Preparations to shutdown a coil include:

1. Sparging cooling water from the coil
2. Drying the coil interior
3. Physically isolating the coil from the cooling water loop

The procedure for restarting a coil that has been shutdown as a result of maintenance depends upon the length of time the coil has been out of service and whether or not the full hydrostatic head has been available from the closed loop demineralized water head tank.

If the hydrostatic head has been available and the downtime is < 72 hours then the coil can be brought straight back into service providing both outlet gamma monitors trips have been tested just before start up and shown to be operational.

If the hydrostatic head has not been available and the down time is < 72 hours then a pressure decay test will be performed and depressurization will be through an activity in air monitor. If the time is > 72 hours then the gamma monitors and trips must be tested in addition to the above. Also the initial cooling water outflow must be limited to an active drainage-sentencing route and monitored for a period.

Note. The figure of 72 hours relates to BNFL’s BUS experience. The exact time for TWRS-P has still to be determined. It relates to the specific activity and physical properties of the liquor, the coil volume and the time estimated for a significant amount of liquor to have migrated into the coils through a postulated small hole. The source term in the UK example is approximately ten times greater than the TWRS source term. (Cs- 189 Ci/e.) (Open Issue)

### 3.5.4.3.4. Area radiation monitor

An operational requirement prior to entry into the operating area associated with the cooling water loop will be to ensure that the area radiation monitor is operating. If it is not operating, a portable unit must accompany the worker. The worker is required to evacuate the area following alarm of the area radiation monitor. The operator must receive training in radiation protection, ALARA programs, and emergency action. The operating area gamma detector will require periodic inspection, testing, and calibration. Radiation control technician support will be provided during these activities. **Operational Assumption.**

### 3.5.4.4 Administrative Standards

Operation of the TWRS-P facilities shall be conducted in accordance with proven practices from BNFL operations in the UK and the US. Arrangements will be in place to maintain and demonstrate compliance with all Safety Criteria detailed within the authorization basis.

Administrative arrangements will provide the framework for how facility operations will be conducted for all modes of operation, including normal, maintenance, or emergency preparedness.

The conduct of operation guidelines will be generated by the tailored application of appropriate sections of the following standards:

IAEA 50-C-0: Code on the Safety of Nuclear Power Plants Operation.
DOE order 5480.19 "Conduct of Operations Requirements for DOE Facilities".
DOE order 4330.4B "Guidelines for the Conduct of Maintenance at DOE Nuclear Facilities".
"Appropriate standards" from the Institute for Nuclear Power Operations.

This framework of conduct will be implemented through:

- Management and organizational structure.
- Documents, records, and certification, including response to abnormal operating conditions, key compliance recording and archiving.
- Structured training programs for all personnel, tailored to their roles and responsibility.
- Emergency preparedness implemented by having an emergency response structure, training, exercises and procedures.
- Incident reporting arrangements.
- Safety documentation hierarchy, with appropriate flow down of information into operational documentation. All safety implications will be clearly identifiable within the operational procedures.
- Quality assurance.
- Arrangements for the examination, inspection, maintenance and testing of all ITS equipment.
- Labeling of ITS equipment clearly on the facility.

### 3.5.4.5 Design Standards

The following section develops the specific standards for the selected SSCs, but has not listed all of the material and minor component standards. Design guides were consulted to establish an appropriate starting point for the designer to identify standards.

#### 3.5.4.5.1. High Integrity Cooling Coils

ASME Boiler Pressure Vessel Code, 1998 Section VIII Pressure Vessels

> ASME BPVC Section VIII is the national standard for the rules for construction of pressure vessels. This code represents mandatory requirements, specific prohibitions, and guidance (not mandatory) for pressure vessel materials, design, fabrication, inspection testing, certification, and pressure relief. Applicable sections of this code will be used for the design of the cooling coil.

#### 3.5.4.5.2. Low Range Gamma Detector

| | |
|---|---|
| ANSI/ANS N4218 | Specification of On-Site Instruments |
| NF 0007/1 | Cooling Water and Steam Condensate Activity Monitoring |

#### 3.5.4.5.3. Area Radiation Monitor

| | |
|---|---|
| 10 CFR 835 | Occupational Radiation Protection |
| ANSI/ANS N4218 | Specification of On-Site Instruments |
| NF 00071/2 | Airborne Activity Monitoring |

### 3.5.4.6 Standards Not in the Safety Requirements Document

The following standards are not in the SRD (BNFL Inc. 1998d).

| | |
|---|---|
| ANSI/ANS | N4218 Specification of On-site Instruments |
| NF 0007/1 | Cooling Water and Steam Condensate Activity Monitoring |
| NF 00071/2 | Airborne Activity Monitoring |

## 3.5.5 Control Strategy Assessment

### 3.5.5.1 Performance Against Common Cause and Common Mode

The strategy has specific performance requirements to ensure adequate safety with respect to wind, wind missile, and seismic event. These are achieved through the selected standards for the building structure and the cooling coils.

Performance requirements have also been set against the identified common cause issue of power failure. The low-range gamma detector and area radiation monitor will have battery backup for continued operation upon loss of power. These details will be confirmed during design development.

### 3.5.5.2 Comparison with Top Level Principles

As a final test, the preferred control strategy - high integrity coil, low range gamma detections with interlocks, area radiation monitor, and restart procedures are evaluated against a set of relevant top level radiological, nuclear, and process safety standards and principles (DOE/RL-96-0006), as laid out below.

#### 3.5.5.2.1. Defense in Depth (DOE/RL 1998, 4.1.1)

Defense in depth is one of the general radiological and nuclear safety principles in DOE/RL-96-0006. SRD Volume II, Appendix B contains the BNFL *Implementing Standard for Defense in Depth*. This Implementing Standard governs application of the defense in depth principle on the TWRS-P project.

To satisfy the application of defense in depth, the Implementing Standard requires that the elements of the control strategy must ensure "…that no one level of protection is completely relied upon to ensure safe operation. This safety strategy provides multiple levels of protection to prevent or mitigate an unintended release of radioactive material to the environment."

DOE/RL-96-0006 formulates the defense in depth principle in terms of the following six sub-principles:

- Defense in depth
- Prevention
- Control
- Mitigation
- Automatic Systems
- Human Aspects

SRD Volume II, Appendix B contains the BNFL Implementing Standard for Defense in Depth. This implementing standard governs application of the defense-in-depth principle on the TWRS-P project and addresses each of the six sub-principles in DOE/RL-96-0006. The following paragraphs describe application of the Implementing Standard for Defense in Depth to the control strategy for cooling water contamination.

1. Defense in Depth (DOE/RL-96-0006, 4.1.1.1)

DOE/RL-96-0006, Section 4.1.1.1 requires the following:

"To compensate for potential human and mechanical failures, a defense-in-depth strategy should be applied to the facility commensurate with the hazards such that assured safety is vested in multiple, independent safety provisions, not one of which is to be relied upon excessively to protect the public, the workers or the environment. This strategy should be applied to the design and operation of the facility." (DOE/RL-96-0006, Section 4.1.1.1)

Section 3.0 of the BNFL Implementing Standard for Defense in Depth addresses this aspect of the defense in depth principle specifically. For SL-1 events, Section 3.0 of the *Implementing Standard for Defense in Depth* requires:

- Two or more independent physical barriers to confine the radioactive material

- Application of the single failure criterion
- A target frequency <1.0E-6/y for the Sl-1 consequences.

The control strategy includes two physical barriers against the release of radioactivity to the environment. The first barrier is the cooling coil within the vessel. The second barrier is the intermediate cooling system piping.

The single failure criterion in the Implementing Standard requires that, given an initiating event, the control strategy must be able to tolerate a single active failure in any active component in the short term. The control strategy must also be able to tolerate a single passive failure in the long term. The single passive failure is to be a mechanistic failure (for example, pump seal leakage); the single passive failure is not a deterministic failure (for example, a pipe break).

The initiating event in this example is failure of the cooling coil in a way that introduces large amounts of process liquor into the cooling coil. The control strategy depends on the integrity of the cooling coil, water quality controls, and startup procedures to preclude such failures. The strategy includes a low range gamma detector with interlock and area radiation monitor to provide indication of pinhole failures in the coil. These instruments satisfy the Implementing Standard single failure criterion.

The analysis in Section 3.5.5.6 shows that the control strategy reduces the frequency of SL-1 level consequences from cooling coil failure to less than $4 \times 10^{-7}$/y. This satisfies the target frequency in the Implementing Standard.

The analyses in Section 3.5.5.3 and 3.5.5.4 show that the control strategy reduces the potential consequences from failure of the high integrity coils to SL-4 levels. The frequency of such failures is $<1 \times 10^{-3}$/y, which is well within the Implementing Standard target frequency of $1 \times 10^{-1}$/y for SL-4 events.

Based on the results of the frequency estimate, the control strategy meets the target frequency with margin. Also, the frequency estimates indicate that the control strategy does not place excessive reliance on any single element to achieve this result.

2. <u>Prevention (DOE/RL 1998, 4.1.1.2)</u>

The primary means of preventing the event is the high integrity of the coils that gives an acceptably low frequency of a leak.

3. <u>Control (DOE/RL 1998, 4.1.1.3)</u>

The frequency of demands placed on the active controls (gamma detector and interlock on the cooling water line and the area radiation monitor) is low due to the integrity of the coils and the inherent process control required to produce specified quality glass.

1. <u>Mitigation (DOE/RL 1998, 4.1.1.4)</u>

Area radiation monitoring and the low range gamma detector provide mitigation by alerting workers to new radiation sources or contamination. The water quality and restart procedure detect and prevent contamination of the intermediate cooling loop. The Radiation Protection Program, ALARA program, along with personnel training on emergency preparedness, will provide additional mitigation.

4. Automatic Systems (DOE/RL 1998, 4.1.1.5)

The low range gamma detector and area radiation monitor are provided to detect elevated radiation exposure rates. The gamma detector automatically isolates the activity. The automatic alarm from either, coupled with appropriate worker response, will also provide facility worker protection.

5. Human Aspects (DOE/RL 1998, 4.1.1.6)

One of the control strategies, the low range gamma detector and interlock on the cooling line, was specifically included to mitigate the consequences of an unprotected facility worker exposure. The human aspects associated with a cooling water contamination event follow proven examples and will be executed within the project procedures for training, qualification, and quality assurance.

Since the Severity Level for the cooling water contamination hazard is SL-1, per Section 2.6.2 of the *Implementing Standard for Defense in Depth*, the control strategy must be reviewed against the human factors engineering criteria in IEEE Std. 1023-1988, 6.1.1, as tailored by the *Implementing Standard*. **Open Issue**.

### 3.5.5.2.2. Operating Experience and Safety Research (4.1.2.4)

All of the adopted methods, including high integrity coil, low range gamma detector interlock and delay tank system, area radiation monitor, water quality, and restart procedures, build on both UK and US operating experience (see Section 3.5.1.4).

### 3.5.5.2.3. Proven Engineering Practices (4.2.2.1)

The design of all of the selected control strategies, including high integrity coil, low range gamma detector and interlock, area radiation monitor, water quality, and restart procedures, are based on proven equipment and practices (see Section 3.5.1.4).

### 3.5.5.2.4. Common Mode/Common Cause Failure (4.2.2.2)

A potential common cause failure is a seismic event. Without any component being seismically qualified, a seismic event could cause a cooling coil leak and loss of cooling water flow in the coil, and subsequent filling with vessel liquor. Subsequent restart of flow could move the slug of liquor out to the detector, which could also fail during the seismic event. Seismic qualification of the cooling coil prevents the initial step in this chain of events. Both the low range gamma detector and area radiation monitor will have battery backup to address the common cause of loss of power. No specific common mode weakness has currently been identified for the selected control strategies. The analysis will continue as the design detail develops.

### 3.5.5.2.5. Safety System Design and Qualification (4.2.2.3)

The operating conditions for the SSCs are known and will be fully addressed by their design. Effects such as aging are well characterized for equipment of the type selected.

### 3.5.5.2.6. Radiation Protection Features (4.2.3.2)

All of the selected control strategies, including high integrity coil, low range gamma detector and interlock, area radiation monitor, water quality, and restart procedures, were selected in part due to their ability to provide radiation protection to the facility worker. The control strategies prevent or mitigate radiation exposure to the facility worker after a significant cooling coil leak. An initial ALARA Review was performed which identified the high integrity line as an increase to radiation protection, while the remaining strategies were judged to be neutral (BNFL 1999).

### 3.5.5.2.7. Deactivation, Decontamination, and Decommissioning (4.2.3.3)

The coils and low range gamma radiation detectors constitute items that will require decontamination and/or disposal during plant deactivation and decommissioning but are insignificant in either volume or complexity. Final design of the equipment will incorporate features to minimize required decontamination and ease decommissioning.

### 3.5.5.2.8. Emergency Preparedness – Support Facilities (4.2.4)

The selected control strategies have no foreseeable impact on the control room or any staffed emergency response center that will be activated after an event.

### 3.5.5.2.9. Inherent/Passive Safety Characteristics (4.2.5)

The high-integrity cooling coil provides passive safety. The gamma detector and interlock have fail safe characteristics.

### 3.5.5.2.10. Human Error (4.2.6.1)

The active systems of the low range gamma detector and interlock and area radiation monitor are designed to the degree possible to mitigate the possibility of human error. The administrative controls will provide redundant checks and verification of conditions prior to proceeding.

### 3.5.5.2.11. Instrumentation and Control Design (4.2.6.2)

Instrumentation is provided to detect any radioactively contaminated cooling water. Radiation monitoring in the operating area alerts the operator of direct radiation. Pressure, flow and/or water quality monitors detect a change in conditions that potentially allow the flow of contamination into the closed loop cooling system.

### 3.5.5.2.12. Safety Status (4.2.6.3)

The selected strategies are unlikely to have a significant bearing on control room safety status display.

### 3.5.5.2.13. Reliability (4.2.7.1)

Reliability targets have been assigned for important to safety SSCs in Section 3.5.4.1. The use of potentially more reliable external vessel cooling jackets vs. internal cooling coils is identified as an **Open Issue** in Section 3.5.6.

#### 3.5.5.2.14. Availability, Maintainability, and Inspectability (4.2.7.2)

To the degree possible, SSCs important to safety are designed and constructed for appropriate inspection and testing. No maintenance or inspection will be possible on the cooling coils after installation in the vessel. The design, as discussed in this example, will require installing redundant coils in the vessel to allow a leaking coil to be sealed off and abandoned in place in the vessel. The design provides for all active SSCs to be outside of the cell.

#### 3.5.5.2.15. Pre-Operational Testing (4.2.8)

The control strategies are amenable to pre-operational testing of their elements, and experience of this exists for these elements.

### 3.5.5.3 Mitigated Consequences

Calculation of the mitigated dose assumed only very small leaks into the intermediate cooling loop, which were less than the lower detection limit of the low range gamma detector, the prime mitigation feature. **Design Assumption.** The consequences are developed in Calc-W375 HV-NS00002 (Smith). Following is a summary of the results.

<u>Facility Worker</u>

The direct worker dose is negligible because these type gamma detectors detect radiation levels on the order of $1 \times 10^{-6}$ rem/h.

<u>Co-located Worker</u>

Dose from radiation shine is negligible.

<u>Public</u>

Dose from radiation shine is negligible.

### 3.5.5.4 Frequency of the Mitigated Event

The frequency estimate for the mitigated release (i.e., at worst, only a pinhole leak develops) is based on crediting the equipment and administrative features cited in Section 3.5.4 and consideration of typical common cause failure probabilities such as loss of power. Human error rates from the reliability information sources cited in the introduction section to the Category 2 examples are also considered. Consideration of all these factors results in an estimated frequency for the mitigated accident of $<1 \times 10^{-3}$/y.

### 3.5.5.5 Consequences with Failure of the Control Strategy (Including Mitigation)

This is equivalent to the unmitigated consequences already discussed in Section 3.5.2.3.

### 3.5.5.6 Frequency of Control Strategy Failure

The frequency of failure of the entire control strategy, including the use of high integrity coils, the required administrative procedures/controls, backed up by on-line radiation detectors, is estimated at 2.4 4 x $10^{-7}$/y and is equivalent to that cited in Section 3.5.4.1.

In summary, the results for this event are shown in the following tables:

**Summary of Results (Mitigated*)**

| **Population** | **Dose (rem)** | **Severity Level** | **Frequency** |
|---|---|---|---|
| Facility Worker | negligible | SL-4 | 1 x $10^{-3}$ |
| Co-located Worker | negligible | SL-4 | 1 x $10^{-3}$ |
| Public | N/A | N/A | N/A |

* Limits failure to a small leak

**Summary of Results with Failure of Control Strategy**

| **Population** | **Dose (rem)** | **Severity Level** | **Frequency** |
|---|---|---|---|
| Facility Worker | 18,000 | SL-1 | 2.4 x $10^{-7}$/y |
| Co-located Worker | 3 | SL-3 | 2.4 x $10^{-7}$/y |
| Public | N/A | N/A | N/A |

## 3.5.6 Conclusions and Open Issues

### 3.5.6.1 Conclusions

A control strategy and associated SSCs and standards have been developed that are capable of providing an acceptable level of protection against the potential hazard of a cooling water contamination event. The control strategy is summarized in Table 3.5-6.

### 3.5.6.2 Open Issues

A number of open issues have been identified for further investigation and resolution as part of design development. These are:

1. Potential Vessel Overflow due to a Cooling Coil Leak. A cooling coil leak could result in two different scenarios: (a) leakage of the vessel contents into the cooling water, or (b) leakage of cooling water into

the vessel. Case (a) has been evaluated in this example. In Case (b), cooling water leaks from the coil to the vessel, with no radioactivity being detected in the cooling water line. The in-leakage of water could cause the waste volume in the vessel to increase until the level of the waste reaches the process vessel vent line. Contamination would then spread to the ventilation system. Alternately, a vessel overflow line could be designed to direct flow to an overflow tank, to the cell floor and/or sump. Overfilling of the vessel could occur due to multiple causes, including operator error, instrument failure, etc. The control strategy for prevention and mitigation of vessel overfilling will have to be an integrated solution of all causes.

2. Use of Cooling Jacket vs. Cooling Coil. A water cooling jacket on the exterior of the vessel could potentially provide a means of cooling the vessel contents with less probability of cooling water contamination than internal cooling coils. The vessel wall has to breach to contaminate the cooling water. Further design will determine if cooling jackets could provide adequate cooling capacity.

3. Potential Dose to a Maintenance Worker. A cooling water contamination event could deposit radioactivity in cooling water system components. Upon opening the system, a maintenance worker could be exposed to the deposited contamination via both inhalation and direct exposure pathways. A control strategy has been developed as mitigation against this event. However, the consequence analysis has been performed for only direct radiation from this event. The need for consequence analysis for inhalation exposure should be reviewed as design progresses. Maintenance activities on potentially contaminated components considered in the Radiation Protection Program, the ALARA Program, and provisions for maintenance of contaminated components will require consideration during design, as well as during operation.

4. Self Heating or Hydrogen Generation. The contents of the V32004A/B vessels will vary depending on the waste available to process. If the waste contained a majority or was all Cs/Tc concentrate, there could potentially be enough decay heat to cause boiling if active cooling is not provided. A loss of cooling and vessel boiling has been evaluated for the Tc and Cs storage vessel in Section 3.2 (Example No. 2). Abnormal operation could cause a change in chemistry and the potential for hydrogen generation. Hydrogen generation in vessels has been evaluated in Section 3.1 (Example No. 1). Both the supporting calculations and proposed control strategies from Examples No. 1 and 2 will provide a starting point for analysis and design.

5. Review Control Strategy Against IEEE Std. 1023. The control strategy must be reviewed against the human factors engineering criteria in IEEE Standard 1023-1988, 6.1.1.

6. Addition of Nitric Acid/Sodium Nitrate. Cooling coil corrosion at Sellafield has been found to be dependent on 3 factors: presence of chloride ion, susceptible site, and peroxide buildup. The chloride ion will be removed through water quality treatment. Peroxide will be removed by flushing. Either nitric acid or sodium nitrate will passivate the surface layer of stainless steel, thereby removing the susceptible site. Further design of the cooling water loop will review and incorporate the latest corrosion inhibiting information.

7. Maximum Cooling Water Downtime. Calculations will need to be performed to determine the maximum cooling water downtime permissible before formal cooling coil restart procedures are involved.

In addition to the open issues listed above, various design and operational assumptions are highlighted in the report. Their continuous validity will be monitored through design development.

## Table 3.5-6. Control Strategy Summary

| **Hazard Description:** Cooling Water Contamination | | | | | **Initiator:** Seismic, Corrosion, Erosion, Weld Failure |
|---|---|---|---|---|---|
| **Selected Control Strategy** | **Important-to-Safety SSCs** | **Safety Functions** | **Design Safety Features** | **Design Assumptions** | **Operational Assumptions** |
| High Integrity Coil | Cooling Coil<br><br>Head tank with sufficient barometric head | Provide process cooling to the vessel while preventing loss of any vessel contents<br><br>Provides higher pressure in coil than in vessel | Seismically qualified<br>Material selection<br><br>Elevation<br>Level alarm | | Water quality maintained<br><br>Operations stop if water pressure lost |
| Low Range Gamma Detector, Interlock, and Delay Tank System | Gamma Detector<br>Detector housing<br>Interlock<br>Delay tank | Provide detection of low range contamination to alert workers of contamination within the cooling loop, shuts down cooling water flow before substantial contamination travels around circuit | Fails in revealed manner, battery backup to detector<br>Functional testing<br>Alarm<br>Volume providing adequate timing | Low detection capability achievable with low background location or sufficient shielding | Calibrate as needed |
| Area Radiation Monitor | Area Monitor & Alarm | Reveal above background radiation levels and alarm at a given set point | Fails in revealed manner<br>Operational status required prior to entry to monitoring room, battery backup | | Workers trained for proper response |
| Water Quality and Restart Procedures | Intermediate cooling loop<br>Water quality instrumentation or sample points | Water quality is maintained for optimum corrosion protection<br>Long-term stagnant conditions prevented<br>QA program and training | Cocooned coils have fail safe leak detector | | Workers trained for proper operations and out-of-normal condition responses |

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Lihou, 1997, WVP Line 3 Calculation, "Supporting Information for PCmSR HAZAN C3.4 – Activity Breakthrough into Cooling Water", February 1997.[b]

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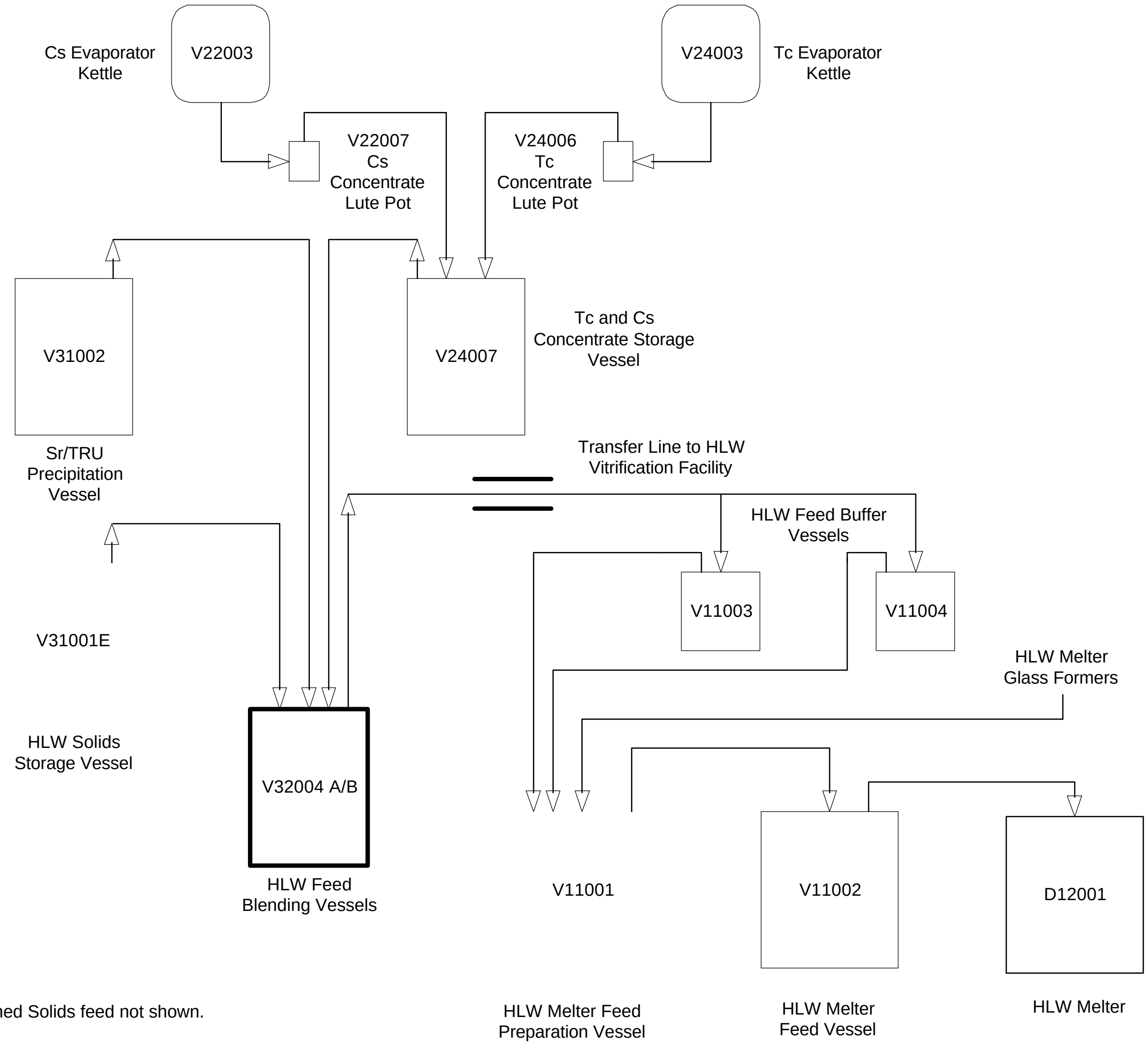
a Copies of these references accompany this deliverable.
b For access to these documents contact the Design Safety Features Point-of-Contact through the office of Safety and Regulatory Programs, TWRS-P, Richland, Washington.

Smith D, 1999, *Cooling Water Contamination*, CALC-W375HV-NS00002, Rev. 0, BNFL Inc., Richland, WA, February 1999.

**Figure 3.5-1. HLW Melter Feed Blending Vessel System.**




Note: Optional Entrained Solids feed not shown.

**Figure 3.5-2. Selected Control Strategies**